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APPLICATION OF ERROR COMPENSATION TECHNOLOGY OF
INERTIAL INSTRUMENTS IN IMPROVEMENT OF STRATEGIC
BALLISTIC MISSILE ACCURACY
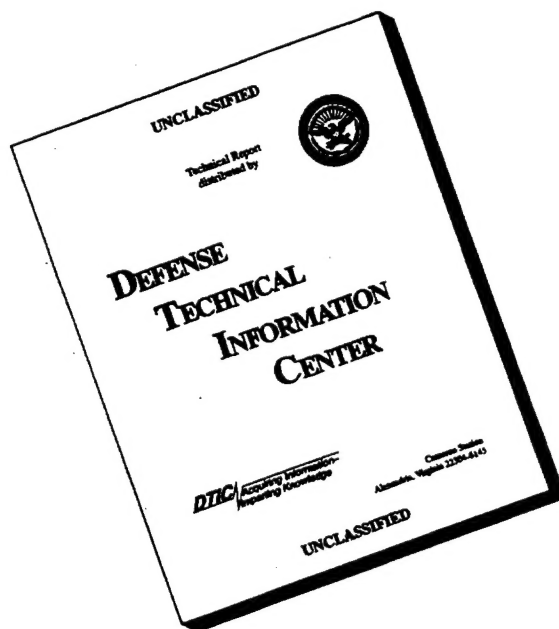
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APPLICATION OF ERROR COMPENSATION TECHNOLOGY OF INERTIAL INSTRUMENTS IN IMPROVEMENT OF STRATEGIC BALLISTIC MISSILE ACCURACY

BY: Zhu Zhenqian

ABSTRACT

This paper presents the classification of inertial instrument primary error sources in ballistic missiles, their effect on accuracy and various methods of error compensation and their individual advantages or shortcomings. Methods used in the United States for intercontinental ballistic missiles are also introduced.   Finally,   several   inertial instrument   error   compensation   schemes   are analyzed.

1. Introduction

There are a number of methods for improving the accuracy of strategic ballistic missiles, such as developing new metering elements, improving the accuracy of inertial instruments, using advanced compound guidance schemes, using different types of terminal guidance technology, etc. These methods generally come at a great cost and a fairly long development cycle. An inexpensive and effective method of improving the accuracy of ballistic missiles is inertial instrument error compensation technology.

So-called error compensation technology allows the error to remain, and refers to clarifying the pattern of error generation and transmission, and its effect on accuracy, and then using hardware or software methods to reduce or eliminate the effects of the error, thus attaining the objective of improved accuracy. This is a necessary and effective method of improving ballistic missile accuracy.

The United States and the former Soviet Union used error compensation technology in the process of improving the accuracy of their international ballistic missiles. The United States began research into error compensation technology for their Minuteman missiles of the sixties, and the reduction from the CEP=1.67km for the Minuteman I to the CEP=0.37km of the Minuteman III was primarily due to the use of error compensation technology. The MX missile is a three stage solid fuel missile which the United States placed into service in the late eighties. It has a range of 11,000 kilometers and uses floating ball platform pure inertia guidance and self correction, self calibration technology for error separation and compensation, with CEP=0.09km. This shows that error compensation technology has been fairly well perfected. The former Soviet Union early strategic weapons had poor accuracy, but in the seventies, they developed the SS-17, S-18 and SS-19 missiles, with respective CEP of 0.44, 0.32 and 0.35km. In addition to using other advanced guidance technology, one of the major reason for this accuracy was error correction of inertial instruments.

2. Classification of primary error sources and their effects on accuracy

2.1. Classification of primary error sources affecting missile accuracy

There are many error factors affecting missile accuracy, more than 100 in all. Different error factors must be considered for missiles with varying degrees of accuracy. In general, the greater the requirements for missile accuracy, the more error factors must be considered. For strategic missiles, errors are divided into guidance error and non-guidance error, based on the missile flight segment and the physical background. Guidance error is further

divided into instrument error and method error. Non-guidance error is further divided into residual error, reentry error, target location error and magnetic anomaly error.

Table 1. Primary error sources for initial guidance instruments

1 仪表	2 误差源名称		3 项数	4 符号	5 单位
6 加速度表	零 偏 7		3	$K_{0\alpha}$	g
	标度因数 8		3	$K_{1\alpha}$	g / g
	二阶非线性 9		3	$K_{2\alpha}$	g / g^2
	三阶非线性 10		3	$K_{3\alpha}$	g / g^3
	11 交灵叉敏轴度	零 偏 12	3	$m_{0\alpha}$	g / crossg
			3	$n_{0\alpha}$	g / crossg
		标度因数 13	3	$m_{1\alpha}$	g / crossg
			3	$n_{1\alpha}$	g / crossg
14 陀螺	固定漂移 15		3	R_α	(°) / h
	质量不平衡 16		3	$U_{1\alpha}$	(°) / h / g
			3	$U_{S\alpha}$	(°) / h / g
	非等弹性 17		3	S_α	(°) / h / g
18 平台	初始瞄准误差 19		6	$\Phi_{\alpha\alpha}$	rad / s
	伺服偏差 20		3	e_α	rad / s
	弹性变形 21		6	$P_{\alpha\alpha}$	rad / s / g
			6	$q_{\alpha\alpha}$	rad / s / g
	总 计 22		57		

1. Instrument. 2. Error source. 3. Item number. 4. Symbol. 5. Units. 6. Accelerometer. 7. Zero deviation. 8. Scale factor. 9. Second stage linearality. 10. Third stage linearality. 11. Intersecting axis sensitivity. 12. Zero deviation. 13. Scale factor. 14. Gyroscope. 15. Fixed fluctuation. 16. Mass instability. 17. Unequal elasticity. 18. Platform. 19. Initial sighting error. 20. Servo deviation. 21. Elastic deformation. 22. Total. NOTE: In this table symbols $k_{1\alpha}$, k_{2B},.... angular coordinates $\alpha = x$, y, z, indicated their components on the thee coordinates. The various errors in Table 1 can also be further resolved into even more detailed error factors, but this will not be done here.

Instrument error is a primary error source of inertial instrument error affecting strategic missile accuracy. In Table 1, 57 different errors are listed by nature and classification of error.

2.2. Effects of primary error factors on missile accuracy

Different physical factors generate errors, and they have different effects on missile accuracy. The same error factor will have different effects due to the range, shape of the trajectory and environmental factors. In general guidance errors are the primary errors, and non-guidance errors are secondary. Instrument error frequently contributes to 60 to 80 percent of CEP value. In order to improve missile accuracy, the designers first of all compensate for or eliminate the effects of the primary error sources, and then gradually resolve or neglect the effects of the secondary errors, finally bringing the effects of the overall error sources on the impact point accuracy to within allowable launch deviation. In order to discriminate between primary and secondary error sources and the degree to which they affect accuracy, the size of the effect on the accuracy of the impact point of primary errors was calculated for a hypothetical group of error data for the launch of a 10,000 kilometer minimum energy missile. The results is listed in Table 2.

Table 2. Effect of primary error sources on precision of intercontinental ballistic

	1 仪表及误差源名称	2 纵向偏差 ΔL(m)	3 横向偏差 ΔH(m)
4 惯表性误仪差	加速度表零偏 $1 \times 10^{-5} g_0$ 5	200	30
	加速度比例误差 10^{-5} 6	600	
	加速度互垂度误差 2″ 7	200	
	陀螺零漂 0.02(°)／h 8	400	130
	陀螺与加速度成比例漂移 0.02(°)／h／g 9	700	220
	陀螺与加速度平方成比例漂移 10	200	70
11 初件始误条差	航向对准误差 20″ 12		650
	垂直调向误差 4″ 13	260	90
	制导方程计算误差 14	100	25
	目标定位误差 15	200	200
	引力异常误差 16	50	50
	后效误差 17	200	30
	再入误差 18	300	200
	总误差 19	1170	760
	CEP 值 20	1140	

1. Instrument and name of error source. 2. Vertical deviation ΔL(m). 3. Horizontal deviation ΔH(m). 4. Inertial instrument errors. 5. Accelerometer zero fluctuation ($1 \times 10^{-5} g_o$). 6. Acceleration proportional error (10^{-5}). 7. Acceleration quadrature error (2"). 8. Gyroscope zero fluctuation (0.002(°)/h). 9. Deviation in ratio of gyroscope to acceleration (0.02(°)/h/g). 10. Deviation in ratio of gyroscope and acceleration squared. 11. Initial conditions error. 12. Course alignment error (20"). 13. vertical adjustment error (4"). 14. Guidance program computer error. 15. Target location error. 16. Gravitation anomaly error. 17. Residual error. 18. Reentry error. 19. Total error. 21. CEP value.

We can see from Table 2 that:

a. Inertial instrument error is a primary error source resulting in missile inaccuracy, constituting 70 percent of total error.

b. Within the different guidance errors, consideration should also be given to making corrections for initial conditions error, target location error and gravitation calculation error.

3. Primary methods of compensating for inertial instrument error

Since World War II, inertial technology development has already passed through three generations. At the present time fourth generation products are under development[3]. Gyroscope accuracy has been improved from $12(°)/h$ to $1.5 \times 10^{-5}(°)/h$, improvements of the fifth or sixth order of magnitude. This has been attained primarily by: (1), improving inertial instruments and processing precision; (2), taking steps to improve the environment such as temperature control, maintaining pressure and vibration preventions; (3), establishing error models, and performing error separation and compensation.

The methods of inertial instrument error compensations in general are: Hardware compensation of inertial instrument error, software compensation of inertial instrument error and system level compensation of inertial instrument error.

3.1. Hardware compensation of inertial instrument error

This type of compensation method relies primarily on increasing hardware equipment to compensate for error. In general it is used in the early stage inertial guidance and ship missile systems. For example:

a. Gyroscope monitoring and control technology

So-called gyroscope monitoring and control technology is to use a monitoring and control gyroscope to measure the deviation

rate of the system gyroscope (being monitored and controlled. In general the first gyroscope is one level of magnitude more precise than the second gyroscope. After using monitoring and control technology, the United States MKIII mod 5 system gyroscope random deviation was cut in half.

b. Gyroscope casing rotation technology

This method causes the angular momentum **H** of the gyroscope rotor to reverse regularly, thus causing the gyroscope deviation to average out and attain a certain degree of control. The United States SGN-4 ship inertial system and the Atlas IIIC inertial system both use gyroscope casing rotation technology.

c. Gyroscope moment control technology.

During missile flight, an electrical moment is usually given to the platform gyroscope to use to stabilize the predictable shift coefficient of the gyroscope. The size of the added moment can be calculated in accordance with known gyroscope fixed shift and coefficient of mass imbalance.

d. Accelerometer zero shift off-set

Certain accelerometers are designed with the capability of remote adjustable zero shift factors such as the vibrating string type accelerometer where changing the harmonic frequency of its string can adjust its zero shift.

Error hardware compensation has used the following technologies: Gyroscope angular momentum modulation technology and platform off-set and rotation technology.

3.2. Software compensation of inertial instrument error

So-called software compensation is the use of theoretical analysis and demonstration through much testing to establish an error model for inertial instrument error, and then to use experimental methods to determine the error factors, calculate the effects of the different errors on velocity, position and target accuracy and have these removed by computer on the ground or on the missile. The key to software compensation lies in the accuracy of the error model and the stability of the inertial instrument error.

There are also many methods of software compensation, and they can generally be divided into single instrument error compensation and system level error compensation. The single instrument error compensation can be divided into single error factor compensation and multiple error factor compensation. The system level error compensation can also be divided into pre launch compensation and live time compensation.

3.2.1. Single instrument error compensation

a. Accelerator zero shift compensation

Compensation effect can be achieved by writing an acceleration zero shift value into a computer on the missile. This zero shift value can be added separately to three acceleration component storage devices or the zero shift quality can be directly added to the guidance program.

b. Accelerometer proportional error compensation

Most integrated accelerometers have linear proportional distortion error within a fairly large measurement scope.

Providing the entry port of the computer with accelerometer data times an appropriate factor can correct for this error.

c. Gyroscope static and dynamic error compensation in quick connect system

In quick connect systems a typical dynamic tuning gyroscope error model is composed of ten errors[4]. As shown in Equation (1), static error includes: scale factors(1); non-alignment (2), (3); mass imbalance (4); Intersecting items (5); unequal elasticity (6) and zero shift (7). Dynamic errors include: angular acceleration items (8), unequal inertia (9) and motor coupling (10).

$$-\frac{M_y}{H} = (1 + DSF_x(T))[\omega_x + \alpha_{xz}\omega_y - \alpha_{xy}\omega_z - m(T)a_x - qa_y + na_x a_2 + b_x +$$

$$\frac{A}{H}\dot{\omega}_y - \frac{C-A}{H}\omega_2\omega_x - \frac{C}{M}\dot{a}_\tau\omega_x] \tag{1}$$

The error coefficient in Equation (1) can be determined through repeated experiments on the ground. Its linear acceleration, angular acceleration and angular velocity can be obtained from missiles in flight. Calculating on a computer the separate effects of static and dynamic errors on gyroscope fluctuations, and finally eliminating these effects by attitude angle or carrier velocity and locations.

3.2.2. System level error compensation

In system level error compensation, the error compensation is not carried out on a single instrument, but carried out together when calculating the effects of a number of instruments on the guidance system. This type of compensation can also be divided into pre-launch compensation and live time compensation.

a. Pre-launch compensation

Before the missile is launched, based on predetermined inertial instrument error models, the ground detection error system value and the environmental factors calculated from standard ballistic parameters are used to calculate the effect of the inertial instrument error on impact point error, and vertical and horizontal deviation are separately corrected for. Vertical correction generally uses adjusting the engine turn off time and the flight programmed angle, while the horizontal corrections generally use adjustments to the launch angle changes in the guidance controls. Some consideration should also be given to the cross-linking effects between vertical and horizontal.

- Horizontal

Turn off engine control:

$$K = \overline{K} \pm \Delta K < \varepsilon$$

$$\Delta K = \left[\sum_{i=1}^{a} \frac{\partial \theta}{\partial k_i} k_i \right] M \tag{2}$$

Correction amount computation

Wherein, $\vec{K}$ is the standard launch turn off load

ΔK is the system value turn off load adjusted to the inertial instrument error

$\frac{\partial \theta}{\partial k_i}$ is the amount of deviation in the instrument error coefficient resulting from the launch distance

M is the conversion coefficient from launch range to the corresponding shut off load

K_f is the inertial instrument error factor

- is horizontal

Launch direction angle correction amount calculation is:

$$\Delta A = \frac{\Delta H}{\partial H / \partial A} \quad \Delta H = \sum_{i=1}^{a} \frac{\partial H}{\partial k_i} k_i \tag{3}$$

Wherein,

ΔA is the launch direction angle requiring correction

ΔH is the system value horizontal error calculated from the inertial instrument error

$\partial H / \partial A$ is the horizontal deviation resulting per unit launch angle

This method of compensation is simple and reliable and only requires this analysis and these calculations be done on the ground before launch. Its shortcomings are that environmental factors are not calculated in as actual flight ballistic parameters, error factors are values determined in advanced and compensation precision is not as good as live time compensation. This method was generally used in early model flight testing in order to observe the results of compensation and the stability of the inertial instruments.

b. Live time compensation

Live time compensation involves the real time calculation of the velocity and position error caused by inertial instrument error based on the inertial instrument error coefficient measured on the ground and the environmental factors calculated from actual flight ballistic parameters, and using this error to correct the output of the inertial instrument or directly introducing this into the guidance system turn off and guidance programs to realize error compensation. It may use a group of recursive calculation formulas such as are shown below:

Guidance equation:

$$
\begin{cases}
V_{xn} = V_{xn-1} + \Delta W_{xn} + \dfrac{1}{2}(g_{xn-1} + g_{xn})\tau - \delta W_x \\[2mm]
\alpha_n = \alpha_{n-1} + (V_{xn-1} + \dfrac{1}{2}g_{xn-1}\tau + \dfrac{1}{2}\Delta W_{xn})\tau - \dfrac{1}{2}\delta W_\alpha \tau
\end{cases}
\tag{4}
$$

In this equation, $\Delta W_{\Delta n}$ is the increase in apparent velocity for each calculation cycle τ. δM_{Δ} is the velocity measurement error in each calculation cycle caused by the inertial instrument.

Accelerometer error equation:

$$\Delta \dot{W}_{xa}(n) = \Delta \dot{W}_{xa}(n-1) + K_{xa_0} + K_{xa_1} \Delta \dot{W}_{xa}(n-1) + K_{xa_2} \dot{W}_{xa}^2(n-1) + \cdots \cdots \qquad (5)$$

Reference azimuth error equation:

$$\begin{bmatrix} \Delta \dot{W}_x(n) \\ \Delta \dot{W}_y(n) \\ \Delta \dot{W}_z(n) \end{bmatrix} =$$

$$\begin{bmatrix} 0 & -(\delta_{yz} + \alpha_z + \Phi_z(n)) & \delta_{zy} + \alpha_y + \Phi_y(n) \\ \delta_{xz} + \alpha_z + \Phi_z(n) & 0 & -(\delta_{zx} + \alpha_x + \Phi_x(n)) \\ -(\delta_{xy} + \alpha_y + \Phi_y(n)) & \delta_{yx} + \alpha_x + \Phi_x(n) & 0 \end{bmatrix} \begin{bmatrix} \Delta \dot{W}_{xa}(n) \\ \Delta \dot{W}_{ya}(n) \\ \Delta \dot{W}_{za}(n) \end{bmatrix}$$

In this equation, $\hat{W}_x(n)$, $\hat{W}_y(n)$ and $\hat{W}_z(n)$ are inertial instrument apparent velocity errors caused by reference line errors.

δ, α and Φ are accelerometer installation error, platform initial alignment error and gyroscope fluctuation angle error respectively.

Real time compensation also has different modes of introducing compensation information.

When the compensation information is directly removed from the accelerometer output not allowing the inertial instrument error to be entered into the guidance system it is called inertial measurement error live time compensation.

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When the compensation information is only removed from turn off load and has no part in the closed circuit control it is called live time terminal compensation.

When the compensation information is added to both the turn off and the guidance program for closed loop control it is called live time closed loop compensation.

These different live time compensation modes have about the same compensation effects, generally better than pre-launch compensation.

3.3. Error compensation in U.S. Intercontinental Ballistic missiles

We will only raise two examples here.

a. Minuteman missile

The Minuteman missile is a three stage solid fuel missile developed by the United States in the early sixties. It had a range of 10200-14000 kilometers. The dynamic pressure gas floating free turning gyroscope on the inertial guidance platform had a fluctuation rate of 0.03°/h. The pendulum gyroscope accelerometer had an accuracy of $10^{-5}g_o$, and the Minuteman had an accuracy of 0.37 kilometers. The primary reason for this accuracy was the establishment of an inertial instrument error model and conducting error separation and compensation. The primary steps they took were:

• They conducted large numbers of ground tests, using all sorts of precision testing equipment such as a tilt-table, vibration platform and centrifuge in repeated testing of the different error factors of the inertial instruments. They then revised and defined the instrument error model.

• They used different shaped missile trajectories such as normal trajectory, high trajectory low trajectory, Half-flight trajectory and guidance validation trajectory to test the accuracy of the inertial instruments and to demonstrate the relationship between sky and ground.

• They improved the external ballistics testing equipment, validating the accuracy of the inertial guidance system with precision radar systems, achieving separation of error factors.

• They used high precision inertial guidance systems to evaluate low precision inertial guidance systems, using MX missile floating ball platform to monitor, meter and test the Minuteman III guidance platform system.

• In order to have the inertial guidance systems with an alert mission constantly on-line, they tested the inertial instrument error factors on a regular basis (such as 6min, 7d, 30d, 90d) so they could be compensated during flight.

• They improved the compensation measures, searching for the best compensation results. There was compensation for the gyroscope on the Minuteman I being sensitive to first and second stage acceleration as well as the four stage acceleration sensitivity in the Minuteman III. In the early eighties they also used electrical torque methods to compensate for the gyroscope constant value fluctuation and fluctuation related to the first and second stage.

b. MX missile

This missile has a range of 11,000 kilometers and an accuracy of CEP = 0.09 kilometers. The guidance system uses a third

generation floating ball platform - the advanced inertia reference sphere (MX/AIRS) developed by the Northrop Corporation. The primary instrument precision was gyroscope fluctuation of $1.5 \times 10^{-5} \circ/h$, accelerometer discrimination of $10^{-6} \sim 10^{-7} g$. The reason for such precision in impact point and in the inertial instruments, in addition to precision processing, assembly, the use of the "three flotation" and temperature control technology, another important reason was that the floating ball platform could perform constant self alignment and self calibration. It also performed precision calibration for inertial instrument error.

The advanced inertial reference sphere used the Autonautics Corporation advanced software for self adjusting. It was called "advanced inertial mechanical arrangement (AIM)". Using this software for testing, no other external references were required, and it relied solely on local gravity acceleration and the earths rotational angle signal. Based on the predetermined trajectory, it allowed the inertia reference sphere to continue to turn, allowing the excitation of the various errors of the gyroscope and accelerometer to be excited, and then comparing the accelerometer measured value with the model in the computer, and using a Karman filter's best estimate of the instrument's calibrated parameters to correct the inertial instrument error in order to improve accuracy. For ease of calculation, two Karman filters were used to align and calibrate the accelerometer, gyroscope and platform. Using the vertical component of acceleration error to calibrate accelerometer factors and using the horizontal component of acceleration error to separate and calibrate the gyroscope factors and platform azimuth error.

4. Comparison and effect analysis of error compensation schemes

4.1. Comparison of inertial instrument error compensation schemes

Assuming that inertial instrument properties are stable and other conditions are the same, a comparison of the advantages and disadvantages of the different compensation schemes is:

a. Hardware compensation

Hardware compensation is more complex, and there are definite limitations to compensation precision. Generally compensation is performed at the instrument level, and system level compensation is difficult to attain. However, it can provide guidance systems with fairly precise inertial instruments.

b. Pre-launch compensation

Computation and compensation are both performed prior to launch. This is fairly easy and highly reliable. However, only inertial instrument ground measured values and calculated values for standard ballistics environmental factors are used during compensation. Therefore, there is always an amount of error between the error factor values and the environmental factor calculations.

c. Live time compensation

Calculation and compensation are both performed by a computer aboard the missile. Using ground measured inertial instrument error factors and actual flight ballistics calculated environmental factors, computation of environmental factors is more precise, more precise than pre-launch compensation. However, there are still some ground and air differences in inertial instrument error factors.

3. Real time compensation plus one time activation

In addition to the advantages of real time compensation, this method also has the advantages of one time activation. For inertial instruments, one time activation can improve precision by several times over multiple activation. Therefore, this type of compensation scheme is one of the more accurate at the present time.

e. Real time compensation with introduction of external references

If highly precise external metering equipment can provide live time measurement of the missile's velocity and precision and live time comparison is made with the measurements obtained from the inertial instruments and sent through a Karman filter for signal processing, and real time adjustments are made to the motion parameters of the missile, this will result in better compensation. Because it compensates for inertial instrument error under actual flight conditions, it uses actual flight ballistic calculations of environmental factors. This is the basic reason for the improved accuracy of GPS-inertial composite guidance schemes. Therefore, composite guidance is a compensation schemes which improves missile hit accuracy by using other highly precise metering information to compensate for and correct inertial instrument error. In theory, it will be even more precise than the other compensation schemes mentioned earlier.

4.2. Error compensation effect analysis

The hit accuracy CEP was calculated for uncompensated, pre-launch compensated and live time compensated 10,000 kilometer minimum energy ballistics and the parameters assumed in Table 2.

In order to analyze the effects of compensation, we assume that the various errors listed in Table are either system error or random error. The results are presented in Table 3.

Table 3. Comparison of error compensation effects

误差名称	方案 1		方案 2		方案 3	
	ΔL(m)	ΔH(m)	ΔL(m)	ΔH(m)	ΔL(m)	ΔH(m)
惯性仪表误差	1060	270	320	80	50	15
初始条件误差	260	650	80	200	13	30
其它误差	430	290	430	290	215	145
总误差	1170	760	540	360	221	148
CEP 值	1140		530		217	

1. Scheme 1.   2. Scheme 2.   3. Scheme 3.   4. Name of Error.   5. Inertial instrument error.   6. Other error.   7. Total error.   8. CEP value.

The results in this table indicate that:

a. Under the assumed conditions, pre-launch compensation will compensate for 70% of inertial instrument error, and can result in twice as much impact point precision.

b. The use of inertial instrument error compensation to improve the accuracy of strategic missiles must be done in conjunction with other error compensations in order to achieve the desired results.

5. Conclusions

In China at the present time inertial instrument error compensation has become a major factor affecting strategic missile accuracy. Improving inertial instrument precision is something we

will have to continue to work on. However, improving inertial instrument precision is, after all, limited by a number of things including the level of industrial technology. Therefore, emphasizing the stability of inertial instruments and establishing error models, separating error factors, and compensating for instrument and system level error is an important means of improving the accuracy of strategic missiles. Foreign experience in this is worth our looking into.

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